HYDRAULIC FORCES THAT PLAY A ROLE IN GENERATING FISSURES AT DEPTH

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Throughout the southwestern United States, fissures are observed to develop in sedimentary material in response to ground-water withdrawal. To explain and also to predict their occurrence, the principal driving force must be identified and quantified. The principal driving force on the aquifer (saturated assemblage of solid particles) is the difference between the driving force on the entire bulk material of solids and water together and the driving force on the water relative to the solids. The latter is the seepage force and is directly measurable as the gradient of hydraulic head. What is new in the present paper is a deeper understanding of the role played by the driving force on the bulk material.

In response to pumping an idealized confined aquifer at a constant rate Q, the net driving force on the skeletal frame turns out to be the gradient of excess pore-water pressure (Helm, 1994). The concept of excess pore-water pressure was introduced by soil engineers (Bjerrum, 1969) to represent the difference between the observed transient gradient of hydraulic head and the calculated ultimate steady-state gradient of hydraulic head.

More generally, the so-called steady-state gradient becomes the bulk driving force (Helm, 1994). It can be considered to be essentially a mathematical way to extend to interior points the physical effect of boundary flows (fig. 1) or pressure conditions that may themselves be steady or transient. Under many circumstances, such as pumping at a steady rate, the physically real driving force on bulk material reduces eventually to the familiar steady-state gradient of hydraulic head.

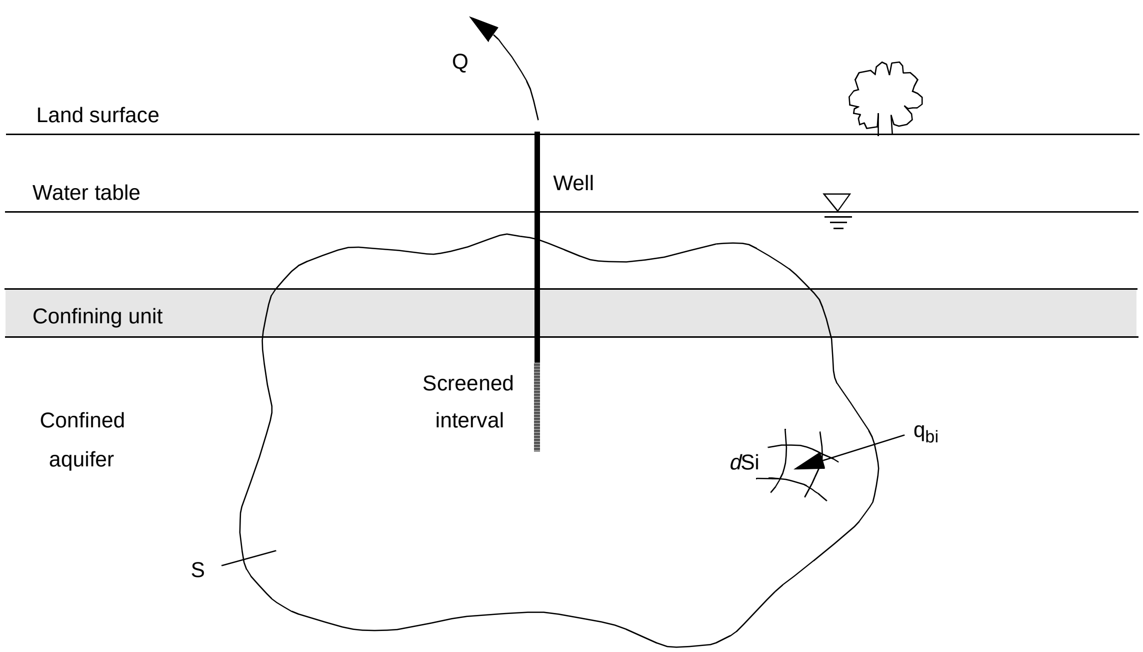

Figure 1. Concept of bulk flux around a pumping well.

The concept of bulk flux can be explained in the following way (see fig. 1). For any arbitrary closed surface S (fixed in space) that contains a sink (such as a screened interval) from which water is being withdrawn at a flow rate Q, if the constituent materials (such as the interstitial water and the grains and platelets that comprise the aquifer) are individually incompressible, then starting immediately upon turning on the pump a bulk flux q_b of solids and/or water must flow through S. This phenomenon is required by the conservation of mass. One can in fact write:

$$Q = \sum_{i=1}^{m} q_{bi} dS_i ,$$

where q_{bi} is the bulk flux moving through an incremented area dS_i and where m such incremented areas compose S. This flow is required through any closed surface within saturated sedimentary material for as long as Q is being withdrawn.

Another result of this analysis is that when a pump is turned on, the aquifer and water together are predicted to be set in motion as bulk flux towards the discharging well. This is a direct consequence of the principle of mass balance and the fact that if the expansion of individual solid grains (which comprise the skeletal assemblage) and the expansion of interstitial water alone are not sufficient to supply the entire flow rate Q from the well, then porosity near the well must decrease (fig. 2). The aquifer skeleton must move inward a sufficient distance and at a sufficient rate so that it remains contiguous. This net movement is also predicted to occur at distant points even where no change in porosity may have occurred locally. In fact, this movement can be quantified.

For the sake of illustration, assume that water and individual grains are much less compressible than the aquifer’s skeletal structure (porosity). Ultimately (after long enough time), the flow rate Q is supplied by steady-state flow of incompressible water past a skeletal frame that has come to rest. Initially, however, Q is supplied by bulk flow as water and the skeletal frame (solids) flow together as undifferentiated incompressible material. In addition, water and solids move initially with the same velocity. As a direct consequence of mass conservation, the bulk material satisfies the equation of incompressible flow throughout time. A major change that occurs with time is that ultimately bulk flow consists entirely of water flowing past solids whereas initially there is no such relative flow. Hence, because there is initially no relative flow (namely, water flowing past solids), there is initially no seepage force. In other words, there is no gradient of observed hydraulic head initially even though the contiguous aquifer is indeed

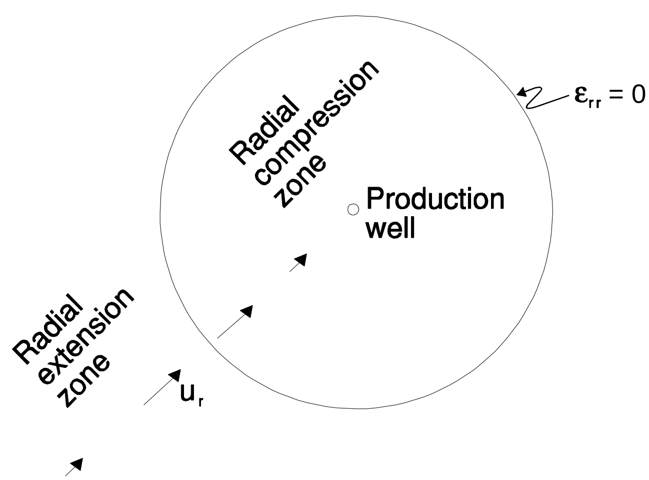

Figure 2. Inner zone of radial compression and surrounding outer zone of radial extension near a production well in a confined aquifer.

moving. During intermediate time, a transient zone of drawdown develops near the well and expands outward (fig. 2). This zone coincides with a zone of decrease in porosity and a zone of relative flow. This zone of drawdown does not, however, delineate the zone of bulk movement itself. To summarize: At any fixed point of interest, bulk movement in a Theis aquifer remains a constant in response to constant Q. It merely makes a gradual transition from flow of solids and water together to flow of water alone.

The process discussed above is illustrated for a confined aquifer in figure 2. The arrows in figure 2 represent the cumulative radial displacement u_r of the aquifer over a specified period of time Δt. Aquifer movement is everywhere inward towards the discharging well. If a front grain travels a shorter distance during Δt than a neighboring back grain travels, radial compression results. If the front grain travels a longer distance than the back grain, radial extension results. For radial compression, the radial strain ε_{rr} (= $\partial u_r/\partial r$) is positive; for extension, it is negative. Along the boundary between the two zones the radial strain ε_{rr} is zero and at this boundary, radial aquifer displacement has reached a maximum (see fig. 2). This boundary itself moves outward with time as the inner zone of aquifer compression gradually expands. Due to axial symmetry, tangential strain $\varepsilon_{\theta\theta}$ equals simply u_r/r and is everywhere compressive. Hence wherever radial extension equals $-u_r/r$ in the outer zone, the sum $\varepsilon_{rr} + \varepsilon_{\theta\theta}$ equals zero and correspondingly there is locally no change in horizontal porosity. Consequently, drawdown in this outer area is unlikely to occur even though the radially inward movement of the aquifer u_r is locally occurring. In fact, in this outermost area of figure 2, u_r can be calculated based directly on the mass balance discussion of figure 1.

The fact that turning on a pump immediately imparts an initial and radially inward velocity onto the skeletal frame has far-reaching consequences. According to Newton's first law, an external force is required to stop the ongoing inward motion of the skeletal frame. Such an external force can be supplied by the well screen itself. It can also be supplied by subvertical heterogeneities within the aquifer with more cohesive or massive material on the far side, for example by distant bedrock intersecting the aquifer at depth. The fundamental question is now reversed. To find how fissures are generated at depth, one must search for forces that impede aquifer movement after the pump is turned on rather than forces that drive it. The natural state of the aquifer is to be moving towards the discharge center—even at distant points where no drawdown is occurring.

Two competing mechanisms have been posited in the past to explain the generation of fissures. They can now be placed in perspective. One of the former explanations (Lofgren, 1978) is the viscous drag of flowing water on a solid particle (fig. 3) caused by horizontal seepage forces (gradients of hydraulic head). Such an explanation is sufficient for an isolated grain, but is incomplete for a radially extensive and contiguous assemblage of grains as has been discussed above. The role of the bulk hydraulic force, which imparts an initial velocity to all particles (namely, both slightly compressible or incompressible fluid particles and incompressible solid particles), has been traditionally overlooked.

The other posited explanation from the past (Lee and Shen, 1969; Jachens and Holzer, 1979) is the horizontal tension caused by flexure of a bending horizontal elastic beam or plate (fig. 4). Bending along the top is caused by an assumed vertical movement along the base of the beam or plate. The center of a subsidence bowl represents the greatest vertical movement beneath the plate, and the perimeter of the bowl represents the least vertical movement. This mechanism qualitatively explains the observed radial inward movement of the land surface.

The bending beam analogy predicts that fissures will occur along the shoulder of a subsidence bowl where horizontal extension is greatest. It also predicts that cracks will open first at the land surface and then propagate downwards. On the basis of on field observations, subsidence-related cracks are universally interpreted to migrate upwards from depth and to express themselves at land surface as a final step. They

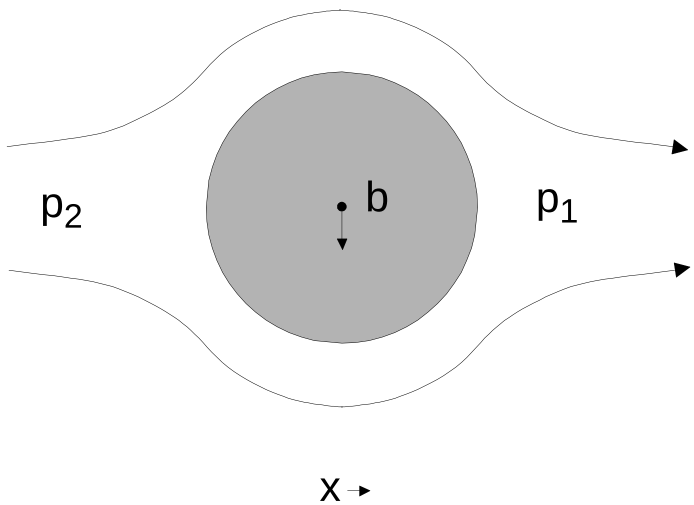

Figure 3. The seepage force analogy: Due to momentum balance, the forces acting on an isolated grain are (1) a submerged or buoyant body force b and (2) a surface force $(p_2\text{-}p_1)/(x_2\text{-}x_1)$ caused, in this case, by the viscous flow of water.

occur not only where predicted along the shoulders of a subsidence bowl where the curvature of vertical movement is convex upward but also beyond the outer perimeter of the subsidence bowl where essentially no subsidence nor drawdown has been observed. Fissures are also found near the center of a subsidence bowl where the curvature of vertical subsidence is concave upward (see Haneberg abstract for additional discussion on fissure migration).

In order to explain this last observation it may seem tempting at first glance to modify the original use of the bending beam analogy. If one considers the entire thickness of an actual bending beam, only the midplane has no horizontal component of movement. Originally, therefore, only the top half of the beam was considered appropriate to apply to the subsidence case. As mentioned above, this allows the base of the traditional bending beam to move vertically only. The modification is to consider the entire thickness. Because the bottom half of an entire bending beam is in extension where the top half is in compression, a tensional crack might conceivably originate at depth near the center of a subsidence bowl, pass through the neutral zone of the midplane and then somehow migrate upward to the land surface through the locally compressing upper half. Such a modification requires the horizontal component of aquifer movement at depth to be radially away from a discharging well. This radially outward motion at depth is opposite in direction from the hydraulic forces and opposite in direction from movement observed at land surface. To require the general horizontal direction of aquifer motion at depth to be away from a discharging well is fraught with insurmountable difficulties. One is left with the original upper-half bending elastic beam analogy (fig. 4) that has had essentially no predictive success.

The bending beam analogy should not be confused with the empirical draping effect. Draping describes the motion at land surface in response to differential vertical movement at depth caused, in turn, by heterogeneities or geologic structure (see Haneberg abstract for a more complete discussion of draping). For example, if gradual vertical slip occurs at depth across a buried subvertical fault due perhaps to different thicknesses of compressing clay on the two sides of the fault, one would expect a corresponding rotational movement at land surface with one side subsiding faster than the other. This would occur due to mass balance whether or not the bending beam analogy is applicable and whether or not elasticity is the appropriate constitutive relation for behavior of unconsolidated sedimentary material.

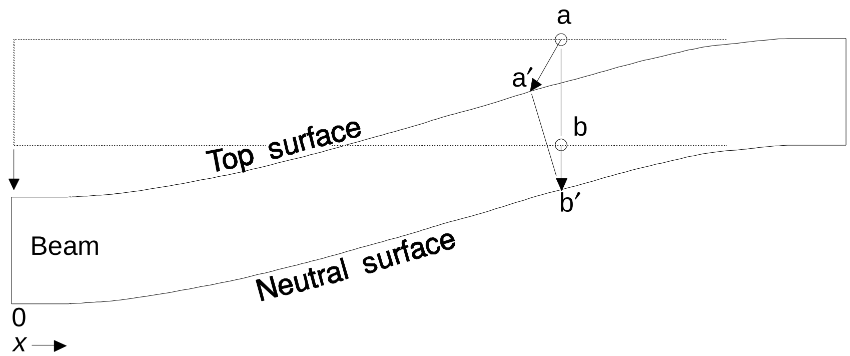

Figure 4. The bending beam analogy: point b on the neutral surface moves vertically downward to a new position b'. Point a, which lies above the neutral surface, rotates both downward and inward towards the point (x=0) where maximum vertical displacement occurs (analogous to the center of a subsidence bowl).

In conclusion, mass balance and Darcy's law for the flow of water relative to the solid matrix require that a porous nonrigid aquifer moves radially towards a discharging well. A bulk hydraulic force allows such movement to occur in outlying areas near the perimeter of a sedimentary basin even before drawdown occurs locally. For known boundary conditions and material properties, this movement can be predicted quantitatively for a continuum. Fissures are predicted to occur where geologic structure and heterogeneities impede this motion and more specifically where preexisting planes or points of weakness allow a crack to be generated.